FRED Reports

COOPERATIVE
ADF&G, FRED DIVISION/U.S. FOREST SERVICE
LAKE ENRICHMENT PROGRAM FOR
SOUTHEAST ALASKA

by
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Alaska Department of Fish & Game
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BACKGROUND

The Alaska Department of Fish and Game (ADF&G) launched the statewide lake enrichment program in 1979. The program was initiated under the Fisheries Rehabilitation, Enhancement and Development (FRED) Division headed up by the Chief of Technology and Development. The program is aimed at rehabilitation and enhancement of sockeye salmon-producing lakes.

Early on, it was decided that a systematic approach to field investigations and decision making regarding the benefits of fertilizer application to lakes be required. A "Guidelines" to lake fertilization was published in 1979 and became the "how to" manual for department staff and cooperators. The guidelines set forth the standards for the types and amounts of data to be obtained from lakes prior to fertilization and, importantly, include the types of information required to judge whether or not fertilizer application has done any good. The latter encompasses what is known as project evaluation. Evaluation is keyed to several benchmarks or trophic responses of the lake ecosystem. These include responses of the phytoplankton (primary production), responses of the zooplankton (secondary production), and responses of the rearing juvenile sockeye salmon (tertiary production). The hypothesis is that addition of nutrients (fertilizer) will result in more food for juvenile sockeye salmon which, in turn, will result in more or larger sockeye salmon smolts which, finally, translates to more adult sockeye salmon.

In conjunction with cooperators, such as the U.S. Forest Service, regional aquaculture associations, and others, lakes that would serve as candidates for study were selected from around the state. Sockeye salmon lakes across Alaska can be crudely categorized according to the appearance of the water within the lake basin: clear, stained or tea-colored, and silty or milky because of intrusion of glacial meltwater. Lakes finally chosen as study lakes included representatives from each of these categories.

FINDINGS

General

Synthesis of research results obtained from lakes around the state formed the basis for the development of predictive models on the carrying capacity and production of sockeye salmon systems. By using performance data from a variety of lakes representing specific lake types, we were able to classify lakes into categories that reflect the limitation to sockeye salmon production. Lakes limited by the low numbers of juvenile recruits able to enter the rearing arena were "recruitment-limited." Lakes limited by the quality and quantity of forage production in the rearing arena were "rearing-limited." Each type of limitation was found to be linked to specific characteristics of the smolt populations (age, size, number) and to the rearing arena (forage, temperature, light). In particular, the rearing-limited lakes were further classified into "forage-limited" and "environment-limited" systems.

We grouped lakes according to numbers of sockeye salmon fry per lake unit (population density) and lake fertility (capacity to produce suitable forage). Production in these two groups of lakes is described and subdivided as follows:

A. Recruitment-limited (low initial input and density of fry)

   1. Escapement-limited (density independent)
   2. Spawning-area-limited (density independent)

B. Rearing-limited (poor lacustrine conditions or fry-forage interaction)

   1. Forage-limited
      a. poor quantity and quality of forage base (density dependent)
      b. poor spatial/temporal concurrence of fry and forage (density independent)

2. Environment-limited
   a. unfavorable temperature regime (density independent)
   b. short growing season (density independent)

The classification indicates that rearing limitations can be (1) either forage- or environment-based or both; (2) that forage limitation can be density dependent or independent; and (3) that density-independent growth can be either recruitment- or rearing-limited.

Use of this lake-classification scheme provides an approach for the matching of the appropriate enhancement strategy (e.g., lake plants of fry or lake enrichment) to the limiting feature of the lake. Our investigations have linked one physical feature of lakes (euphotic volume [EV]) to the base of the food chain and, in turn, to sockeye salmon production. We have distilled out a series of equations that can be used to forecast baseline sockeye salmon production from lakes and to determine numbers of rearing fry. These findings also can be used to establish escapement goals for sockeye salmon lakes.

From experimental manipulations of fry densities, we have developed two predictive equations:

1. Log SW = 5.78 - 1.09 log SD (EV); $r^2 = 0.99$
2. % FWS = 1.89 + 51.86 Log SW; $r^2 = 0.92$

Also, from empirical observations on nursery lakes, we have formulated four relationships:

3. SN = -42,021 + 23,010 EV; $r^2 = 0.97$
4. Log SL = 1.71 + 0.31 Log SW; $r^2 = 0.99$
5. Log Ocean Survival = -2,647 + 0.035 SL - 0.000142 $(SL)^2$; $r^2 = 0.36$
6. ASP = -95,000 + 2,498 EV; $r^2 = 0.95$

   Where: ASP = Adult Sockeye Production
   EV = Euphotic Volume Units (millions of m^3)

SW = Smolt Weight (g)
SN = Smolt Numbers
SL = Smolt Length (mm)
SD = Stocking Density

For nursery lakes capable of supporting density-dependent growth, a stocking density (SD) of $\sim$110,000 fry $\circ$ EV^{-1} would result in forecasting the production of a 1.9-g, age-1.0 smolt (Equation 1). This corresponds to a threshold-sized smolt of 2 g which is then used to estimate a brood-year freshwater survival (FWS) at 18% (Equation 2). The original stocking density of 110,000 fry $\circ$ EV^{-1} multiplied by a survival to smolt of 18% yields a smolt population estimate of 20,000 smolts $\circ$ EV^{-1}. This is very close to the 23,000 smolts $\circ$ EV^{-1} found in the empirical relationship derived from rearing-limited lakes (Equation 3).

The threshold smolt size of 2 g can be converted to an equivalent length (Equation 4) of 64 mm which results in a predicted ocean survival of 10% (Equation 5). That is, the nearly 20,000 smolts $\circ$ EV^{-1} of 2-g size produced by an original stock density of 110,000 fry $\circ$ EV^{-1} forecasts the production of nearly 2,000 adults $\circ$ EV^{-1}. This is consistent with our empirical observations of rearing-limited sockeye salmon systems (Equation 6) that produce 2,400-2,500 adults $\circ$ EV^{-1}. Moreover, the overall ocean-survival estimate is derived from a comparison of Equations 3 and 6; i.e., 2,500 adults $\circ$ EV^{-1} equals 11%. Finally, use of a 2-g-sized smolt population throughout the calculations (outlined above) becomes the model for systems capable of density-independent rearing. Thus, through validating empirical observations with experimental results, a set of equations emerges that are useful in estimating adult production levels from any stocking density based on a lake's euphotic volume and the knowledge of density-dependent versus density-independent juvenile rearing.

By modeling existing sockeye salmon production based on the above approach, we can now define (1) the enhancement approach most likely to result in a positive benefit, (2) the particular information needed to gain access to the model, and (3) a realistic appraisal of expected adult production and the numbers of fry it requires, which are especially useful in both planning and benefit/cost estimates. For example, we have used these results to establish stocking levels, expected smolt production, and adult pieces for a variety of lakes in southeast Alaska, as Table 1 illustrates. Hence, we have an extremely powerful tool for the resource manager.

Specific

Hugh Smith Lake:

The Hugh Smith Lake fertilization study began as a cooperative project with FRED Division, the U.S. Forest Service, and the Southern Southeast Regional Aquaculture Association in 1979. Prefertilization studies were conducted in 1979 and part of 1980. The fertilization phase began in 1980 and continued through 1983 with application during May through September each year. Post-fertilization studies continued in 1984 and 1985. Detailed limnological and fisheries studies to define trophic level changes as a result of fertilizer application were conducted, as outlined in FRED lake fertilization project guidelines.

Findings based on data collected during the 1979 through 1985 study period showed definite increases in primary and secondary production and forage available for rearing sockeye salmon. Even though increases in forage occurred, no increases in sockeye salmon smolt production were observed. That is, size of smolts, growth rates, age composition, and survival of fry to smolt did not change during the study period.

These parameters, in fact, remained relatively constant over a wide (six-fold) variation in density of rearing sockeye salmon juveniles.

This nonresponse of rearing fish to increases in food availability, a response to fertilization, and significant variations in rearing densities lead to the classification of Hugh Smith Lake as a "density-independent" lake. In fact, further studies revealed that temperature is limiting here (B.2.a lake). For some unknown reason, sockeye salmon fry at Hugh Smith Lake behaviorally key to a particular temperature isopleth throughout

Table 1. Lakes in southeast Alaska.

Lake	Area (km^2)	1% light level (m)	EV (units)	Total[1/] spring fry (millions)	Total[2/] smolts (millions)	Total[3/] adult pieces
1 Speel	1.7	-	-	-	-	??????
2 Indian	2.2	8	18	2.0	0.4	45,000
3 Crescent	3.3	9	30	3.3	0.7	75,000
4 L. Sweetheart	5.1	10	51	5.6	1.2	128,000
5 Redoubt	12.8	10	130	14.3	3.0	325,000
6 Chilkat	10.1	13	131	14.4	3.0	328,000
7 Turner	12.6	18	227	24.9	5.2	568,000
8 Heckman	1.6	7	11	1.2	0.3	28,000
9 Old Franks	2.5	5*	13	1.4	0.3	33,000
10 Neck	4.1	4	17	1.9	0.4	43,000
11 Patching	2.1	9	19	2.1	0.4	48,000
12 Hetta	2.1	15	32	3.5	0.7	80,000
13 Klawock	11.8	7	82	9.0	1.9	205,000
14 Woodpecker	0.7	10	7	0.8	0.2	18,000
15 Bakewell	2.9	6	17	1.9	0.4	43,000
16 Hugh Smith	3.2	6	20	2.2	0.5	50,000
17 Badger	2.1	13	27	3.0	0.6	68,000
18 McDonald	4.2	8	34	3.7	0.8	85,000
19 Reflection	3.0	15	45	5.0	1.0	113,000
20 Lake Grace	6.1	15 (est)	92	10.1	2.1	230,000
21 Ella	6.2	15 (est)	93	10.2	2.1	230,000
22 Manzanita	6.3	15 (est)	95	10.5	2.2	238,000

* Mean depth
1/ 110,000 fry $\circ$ EV^{-1}
2/ 23,000 smolts $\circ$ EV^{-1}
3/ 2,500 adults $\circ$ EV^{-1}

the year. This causes a limitation of fry-growth rates and subsequent smolt size independent of fry density and/or forage availability. Thus, fertilization of Hugh Smith Lake, which functions as a density-independent system, was not beneficial for enhancing sockeye salmon production. (Hindcasting, at the outset Hugh Smith was believed to be a B.1.a. lake but, upon investigation, proved to be a B.2.a. lake.)

Studies are continuing at Hugh Smith Lake to determine the feasibility of enhancing sockeye salmon production via introduction of hatchery-incubated fry. Observed adult escapements have not provided adequate recruitment to fully utilize Hugh Smith's rearing habitat. These low escapements are due to continued high harvest levels of these stocks in existing commercial fisheries. Plants of 325,000 and 225,000 fry were made in 1986 and 1987, respectively. These fry were from eggs taken from Hugh Smith Lake and incubated at FRED Division's Beaver Falls Hatchery in Ketchikan.

McDonald Lake:

The McDonald Lake fertilization study began as a cooperative project with FRED Division, the U.S. Forest Service, and the Southern Southeast Regional Aquaculture Association. Prefertilization studies began in 1980 and continued until 1982 when fertilizer application began. Fertilization has continued through 1986 and is planned for 1987.

Detailed limnological and fisheries studies at McDonald Lake have shown definite increases in primary production and limited increases in secondary production. No significant observed changes have occurred in sockeye salmon fry-growth rates, smolt sizes, or age composition during the study period. Although no increase in growth rates of juvenile sockeye salmon were observed, total production has been at a very high level. Rearing densities have been very high with total numbers of outmigrant smolts ranging from 1 to 3 million. Since survival to smolt has remained relatively high during the five years of fertilization, it can be speculated that fish production is being artificially maintained at an elevated level. It also can be argued that other environmental factors are at play; we have no equivocal data. Nevertheless, adult production based on escapement into the lake averaged 80,000 during eight years for which data were available prior to fertilization. The first year for returns that received full benefit of fertilization was 1986 when 120,000 adults escaped to the lake. To the best of our knowledge, commercial fisheries exploitation of this stock has remained constant. Further, our data show an asynchrony between maximums of zooplankton-standing crops (fall) and mid-May fry emergence that is being brought to coincidence by nutrient enrichment. (Hindcasting, at the outset McDonald was viewed as a B.1.a lake, but has proved to be a B.1.b. lake.) We have used the models described on pages 3 and 4 to establish an escapement goal for adult sockeye salmon into McDonald Lake. Fisheries managers are being encouraged to harvest approximately 35,000 more sockeye salmon from this lake.

Present plans call for continuation of fertilizer application and monitoring production at all trophic levels. Coded-wire tagging of McDonald Lake sockeye salmon smolts has identified the stock as a significant contributor to the District 106 gillnet fishery. Due to the importance of the lake in producing fish for existing fisheries and some evidence that fertilization is maintaining a stable production at a high level, fertilization should be continued. This continuation should depend upon available funding levels and future evaluation of production from the system.

Badger Lake Sockeye Salmon Fry-Planting Project:

Badger Lake is the upper lake in the Bakewell Lake drainage. As part of a program to more rapidly develop a sockeye salmon run back to the system after reconstruction of the Bakewell Creek fishway, fry plants were initiated at Badger Lake.

Studies were initiated in 1984 to define the potential of Badger Lake as rearing habitat for juvenile sockeye salmon. The lake was planted with 556,000 sockeye salmon fry in June of 1985 and 515,000 in June of 1986. These fish were from eggs taken from Hugh Smith Lake and incubated at the FRED Division Beaver Falls Hatchery. The initial plants had an excellent survival to smolt (25%) and grew nicely (mean smolt size of 80 mm).

The projected returns from these initial plants are 20,589 adults during the period 1988 through 1989. Presently, Badger Lake operates as an A.1. lake, but with fry plants and adult access it could become a B.1.a system.

Northern Southeast Area

The inclusion of the northern Southeast area into the lake enrichment program occurred in 1980-1981 with the implementation of a lake enrichment feasibility study at six sockeye salmon nursery lakes in this area. The results of this study indicated that Falls and Redoubt Lakes were the best candidates for inclusion into the program.

Detailed preenrichment studies were initiated at Falls and Redoubt Lakes in 1981 and 1982, respectively. Each lake was investigated for two years prior to fertilizer application in order to document the existing fish production (in-lake rearing fry, smolts, and adults) and limnological (physical, chemical, and primary and secondary biological production) characteristics.

Falls Lake:

Fertilizer applications were initiated during 1983 and continued through 1985. Fertilizer was applied at varying rates and intervals between May and September of each year.

The fertilizer applications increased phytoplankton production. This coincided in 1983 and 1984 with increased densities in the zooplankton community. During 1985 the zooplankton densities remained at the relatively low prefertilization level throughout the fertilizer application period, even though 1985 phytoplankton levels were the highest for each of the three years of fertilization.

Although the age composition and total smolt emigration numbers remained relatively stable, the data indicate that there was a significant increase in smolt size (length) between the prefertilization years and the fertilization years. Since smolt size has been identified as having a direct effect on adult marine survival, we can, therefore, surmise that this increase in size will have a positive effect on adults. (Hindcasting, Falls Lake was initially viewed as a B.1.a. system and studies have upheld this view, although the lake does reveal some temperature limitation on fry growth.) Since the adult sockeye salmon returning to Falls Lake are predominately 5- and 6-year-old fish (82%), the adults produced from the 1982 brood (the first brood affected by the fertilizer applications) should begin returning to the lake in significant numbers during 1987 and 1988. The majority of adult fish produced (as smolts) during the fertilization years will return to the lake from 1987 until 1992.

The original plan for the Falls Lake project stated the intention to continue monitoring this lake after the cessation of fertilizer application; however, the current budget climate within the FRED Division forced the shutdown of this project. Interest remains in continuing the support of the efforts of the U.S. Forest Service to monitor the adult escapement to Falls Lake relative to the evaluation of its fish ladder project at this site. The information generated from this monitoring also would be useful in evaluating the adult production resulting from the fertilizer applications made during 1983-1985.

Redoubt Lake:

Fertilizer applications were initiated during 1984 and are projected to continue through two life-history cycles (1998) for the sockeye salmon at this project site. Fertilizer has been applied to the lake at various locations, application rates, and intervals between May and September of 1984 through 1986.

The phytoplankton data for 1984 and 1985 show an increase for all sampling sites. This increase coincided with an increase in observed zooplankton densities. Sample and data analyses for 1986 are still underway.

Quantitative smolt sampling was included in this project since its initiation in 1982. Due to the configuration of the lake outlet and the discharge levels from the lake, numerous smolt-capture methods have been attempted to generate an estimate of total smolt emigration. All of these methods have proven unsuccessful in generating a quantitative estimate of the total smolt emigration from the system. The most aggressive approach to date will occur in 1987. Should this effort fail, we will turn to hydroacoustic estimates and forget about smolt fences.

Age and size of smolts observed since 1982 indicate no specific trends in changes to age composition, but a significant increase was observed in smolt size (length) between the prefertilization and fertilization treatment years. This increase in smolt size can be directly correlated to an increase in marine survival rates, thereby increasing the number of adults expected to return.

The adult sockeye salmon produced from this system are predominately 5- and 6-year-old fish (88%). Therefore, the adults produced from the 1983 brood year (first brood affected by fertilizer application) should begin returning to the lake in significant numbers during 1988 and 1989. Relative to the completed fertilizer applications, adults affected by the fertilizer application will be returning to this lake until 1992.

Using the fisheries and limnology data base generated from this project, Redoubt Lake can be categorized as a density-independent system due to the small forage food base and underutilized rearing habitat (an A.1 system; hindcasting, we believed it to be a B.1.a. system). This lake has the potential to benefit from the continuation of the fertilization program and from artificial plants of sockeye salmon fry. Continuation of the project is strongly linked to delivery of hatchery fry to the system; otherwise, there simply will not be sufficient numbers of salmon fry present in the lake to take advantage of the additional forage produced from enrichment. The current plans for this project are to continue applying fertilizer to the lake and to initiate a fry-stocking project as soon as possible.